



Energy and  
Resources  
Group



# Fuel Cells Today and For Tomorrow:

## Stationary and Mobile Applications and Synergies

December 12, 2002

**EETD/DER Seminar**  
**EO Lawrence Berkeley Lab**  
**Berkeley, CA**

**Dr. Timothy Lipman**

**With:**

**Ms. Jennifer Edwards**

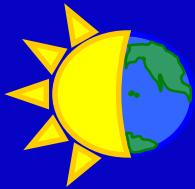
**Prof. Daniel Kammen**



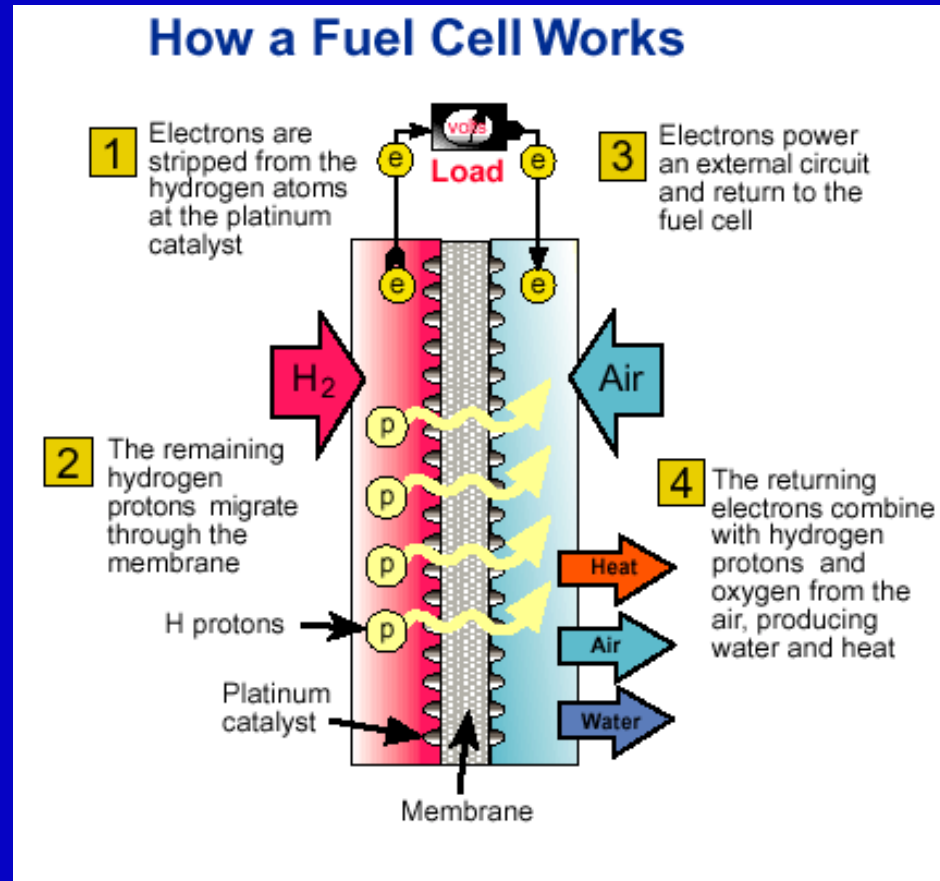
# Talk Outline

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- Fuel Cell Operating Principle (PEM Example)
- Status of Fuel Cells for Vehicles
- Status of Fuel Cells for Stationary Applications
- Hydrogen Energy Station Analysis (CETEEM)
- Fuel Cell Vehicle-to-Grid (V2G) vs. Stationary FC Power (CETEEM)
- New DER Center on UCB Campus - CIDER



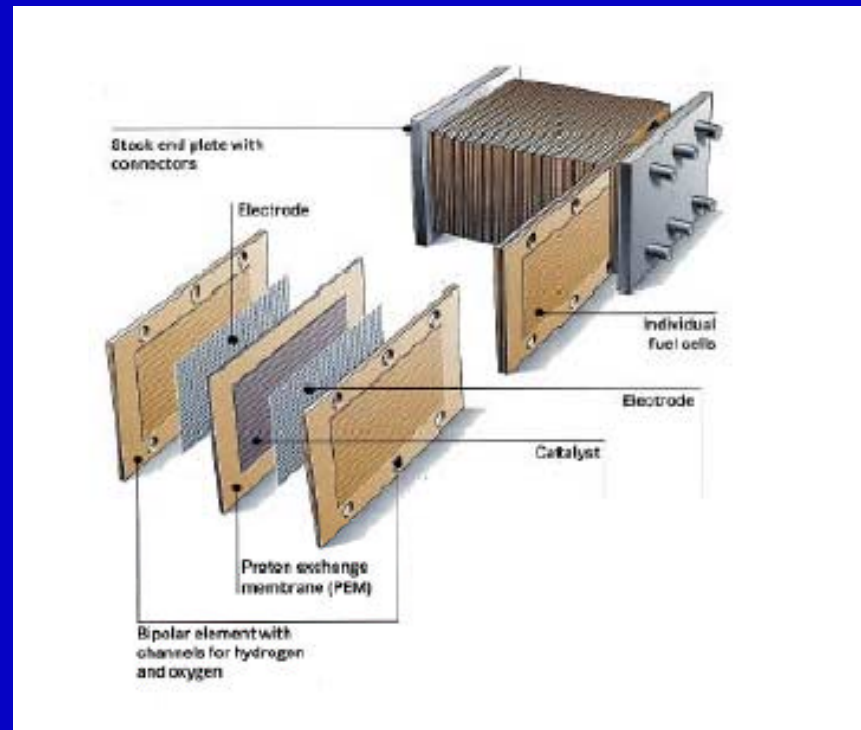
# Fuel Cell Operation (PEM ex.)

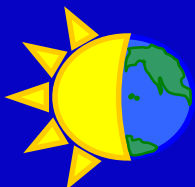




# Fuel Cell Operating Principle

**In most designs, fuel cell plate and cell assemblies are stacked to produce a high voltage system of many cells connected in series**





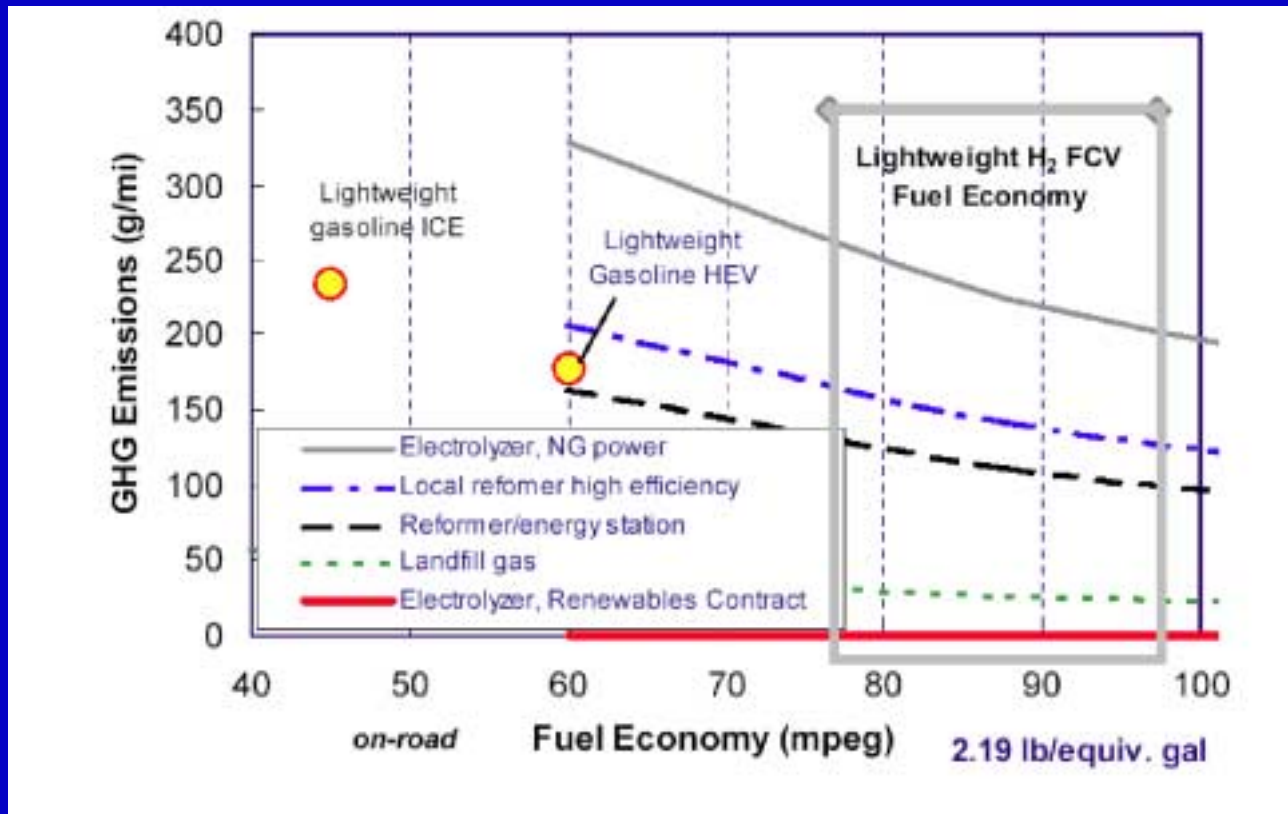
# Fuel Cell Types

	<b>PEFC</b>	<b>AFC</b>	<b>PAFC</b>	<b>MCFC</b>	<b>ITSOFC</b>	<b>TSOFC</b>
Electrolyte	Ion Exchange Membranes	Mobilized or Immobilized Potassium Hydroxide	Immobilized Liquid Phosphoric Acid	Immobilized Liquid Molten Carbonate	Ceramic	Ceramic
Operating Temperature	80°C	65°C - 220°C	205°C	650°	600-800°C	800-1000°C
Charge Carrier	H <sup>+</sup>	OH <sup>-</sup>	H <sup>+</sup>	CO <sub>3</sub> <sup>-</sup>	O <sup>-</sup>	O <sup>-</sup>
External Reformer for CH <sub>4</sub> (below)	Yes	Yes	Yes	No	No	No
Prime Cell Components	Carbon-based	Carbon-based	Graphite-based	Stainless-based	Ceramic	Ceramic
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites	Perovskites
Product Water Management	Evaporative	Evaporative	Evaporative	Gaseous Product	Gaseous Product	Gaseous Product
Product Heat Management	Process Gas + Independent Cooling Medium	Process Gas + Electrolyte Calculation	Process Gas + Independent Cooling Medium	Internal Reforming + Process Gas	Internal Reforming + Process Gas	Internal Reforming + Process Gas



# Fuel Cells and Vehicles

## GHGs for Hydrogen FCVs vs. ICE Vehicles



Source: Bevilacqua-Knight, 2001



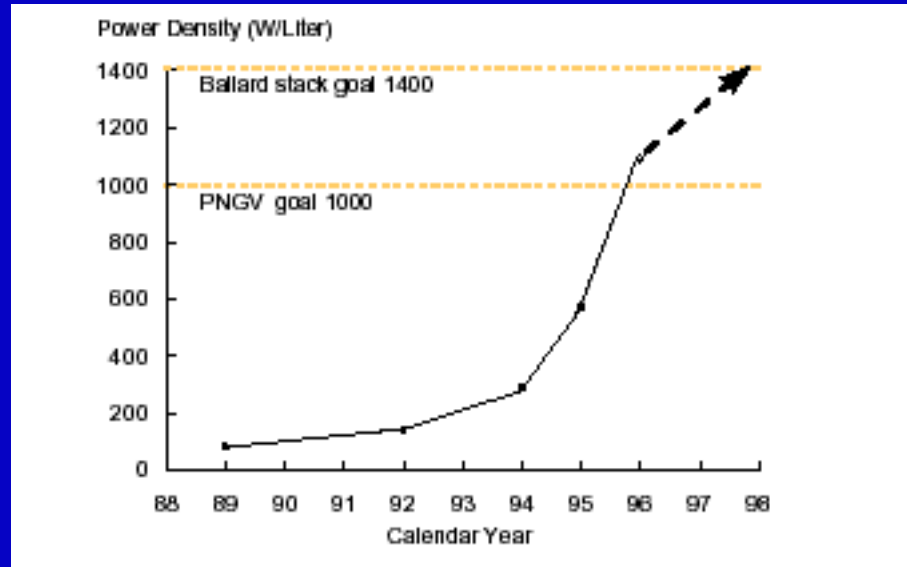
# Fuel Cells and Vehicles

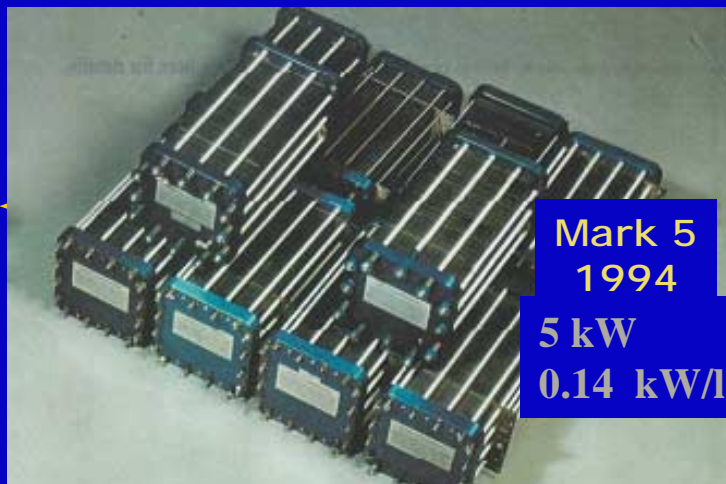
Manufacturer	Recent Prototype Vehicles	Fuel Cell System	Commercialization Timeframe
BMW	H <sub>2</sub> ICE 1.2 - V 750	DMEM APU and Dphi SOFC APU (CH F powered)	Fuel cell APU introduction ca 2006
Daimler	MOV EFC V-K II	To y out Direct-H <sub>2</sub> (hybrid)	Unknown
DaimlerChrysler	NEC A RV FCV NEC A RV FCV Narium FCV Citaro FC Bus	Ballard Direct-H <sub>2</sub> Ballard ME Ballard Direct-H <sub>2</sub> Ballard Direct-H <sub>2</sub>	Limitation of diffusion in 2004
Fiat	Seicento Elettra H <sub>2</sub> FCV	Nuvera Direct-H <sub>2</sub>	Unknown
Ford	Thin Eco Fuel Cell P200 FCV	Ballard Direct-H <sub>2</sub> Ballard Direct-H <sub>2</sub>	Limitation of diffusion in 2004
General Motors	HydroGenOx Zafira FCV Chevy Silverado FCV	GM Stacks 1000 GM Stacks 1000 CHF	Availability in 2005, volume production in 2008-2010, to be first commercial to sell 1 million FCVs
Honda	FCXV 3FCV	Ballard Direct-H <sub>2</sub>	Introduction in 2003, less than a few hundred direct-H <sub>2</sub> FCVs
Hyundai	Santa Fe FCV	IFC Direct-H <sub>2</sub>	Unknown
Mazda	Premacy FC-EV	Ballard ME	Participation in programs with Ford Motor Group and Honda
Mitsubishi	MFCV Concept Vehicle	Mitsubishi MemOx	Working with Mitsubishi Heavy Industries to develop commercial FCV by 2005
Nissan	Renesas SUV Xterra SUV	Ballard ME Ballard ME	Limitation of diffusion in 2003 or 2004, working with Renault to develop commercial FC technology by 2005
Pugeot Citroen			Working with Renault
Renault	FERE FCV	Direct-H <sub>2</sub>	Working with Peugeot/Citroen and Nissan to develop commercially via FCV by 2010
To y out	FC H V4 FCV FC H V5 FCV FC H V8 US 1	To y out Direct-H <sub>2</sub> To y out CHF (hybrid)	Limitation of diffusion in 2003, expect full commercialization ca.



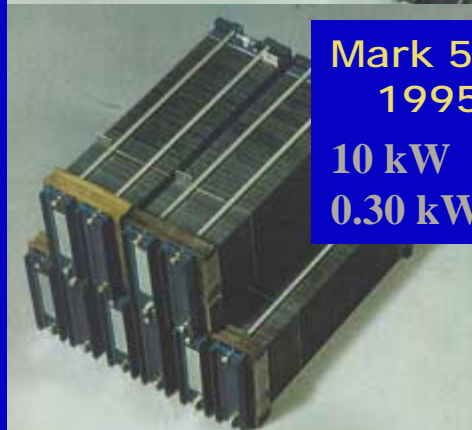
# Fuel Cell Progress

- Power density has increased dramatically in the last decade, e.g. for PEMFC: Ballard technology (figure below) and GM with Stack 2000 (1.75 kW/liter!)

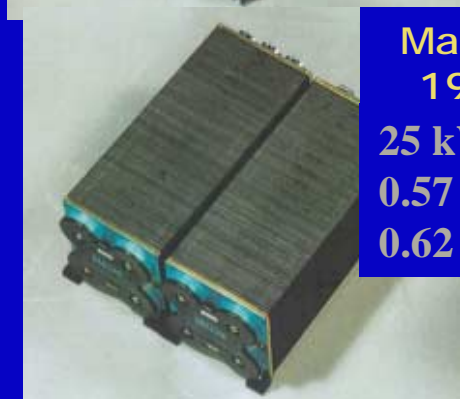




**Mark 5**  
**1994**  
**5 kW**  
**0.14 kW/l**



**Mark 513**  
**1995**  
**10 kW**  
**0.30 kW/l**



**Mark 7**  
**1996**  
**25 kW**  
**0.57 kW/l**  
**0.62 kW/Kg**



## Evolution of Ballard Fuel Cell Stacks



**Mark 8**  
**1997**



**85 kW**  
**Mark 9**  
**2002**  
**1.1 kW/l**  
**0.92 kW/Kg**



**Mark 9**  
**2000**

**75 kW**  
**1.04 kW/l**  
**0.89 kW/Kg**



# Fuel Cells and Vehicles

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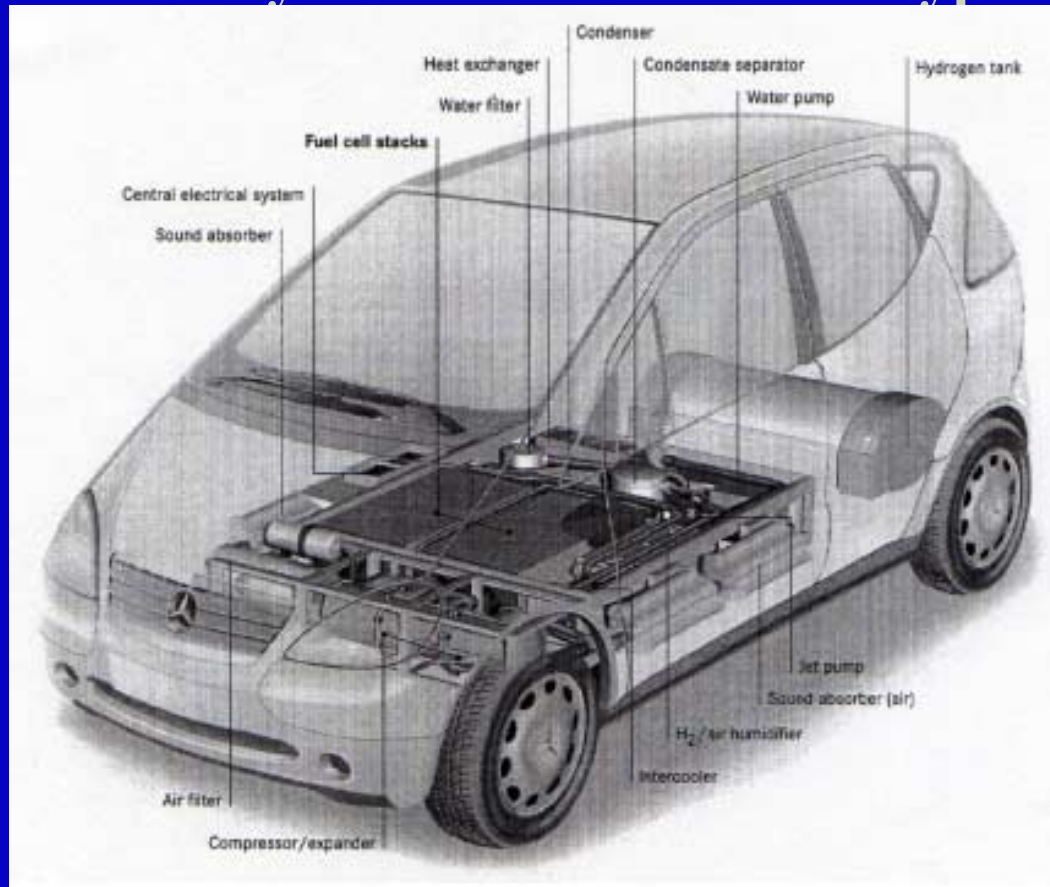
## Early 1990s Daimler Prototype FCVs





# Fuel Cells and Vehicles

## DaimlerChrysler NECAR IV Prototype





# Fuel Cells and Vehicles

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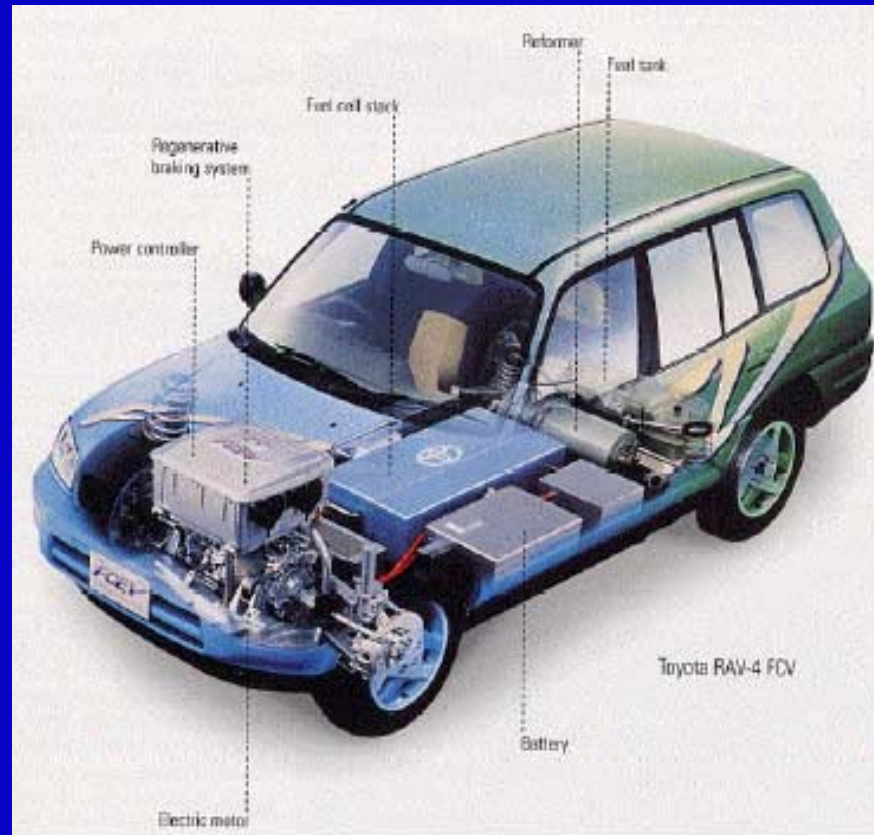


The gasoline processor and other auxiliary components take up about half of the cargo space in General Motors' new S-10 fuel cell pickup truck, the first vehicle shown publicly with a processor that extracts hydrogen from gasoline. The truck is 40% efficient (overall system); more than twice that of an IC vehicle.



# Fuel Cells and Vehicles

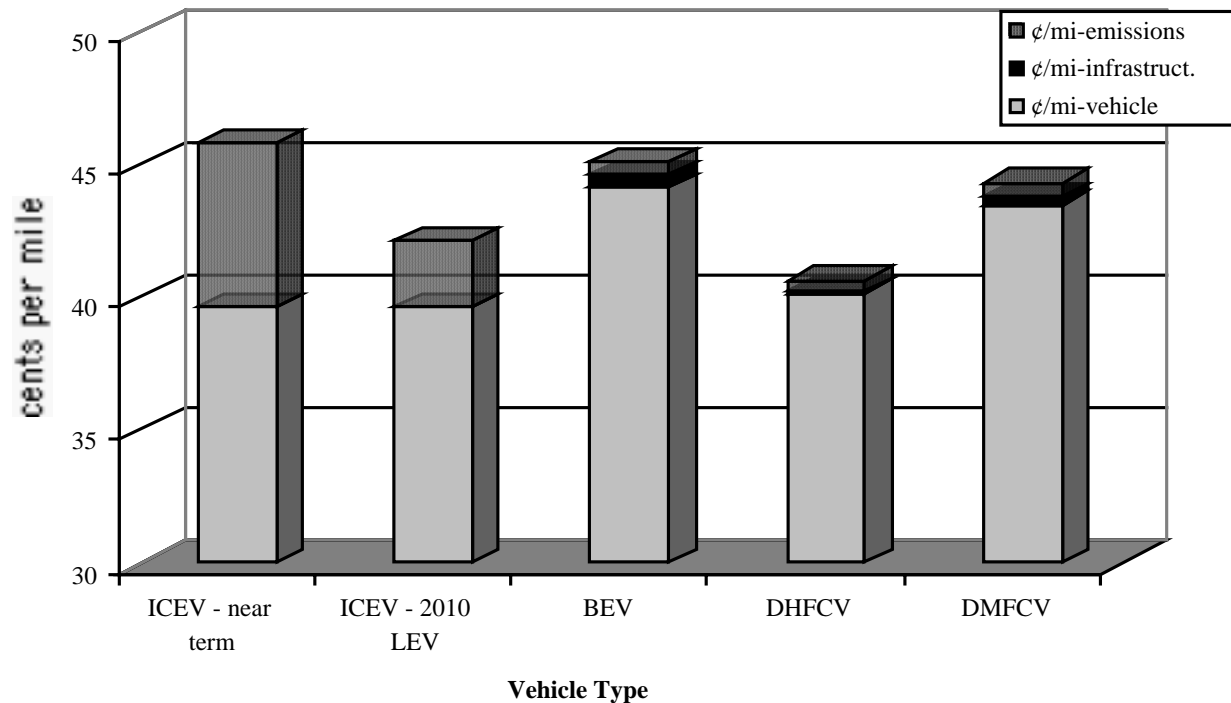
## Toyota RAV-4 FCV Prototype





# Fuel Cells and Vehicles

**Vehicle Lifecycle, Infrastructure, and Emission Costs:  
Year 2026 - High Prod. Volume Central Case (1997¢/mi)**





# Fuel Cells and Vehicles

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- But Not Just Light-Duty Vehicles
- Lots of Activity Around Fuel Cell Buses
- Fuel Cell APUs for Heavy-Duty Trucks
  - UCD/Ballard/Freightliner Demo
- Marine Applications



# Fuel Cells and Vehicles

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- Key Issues
  - Not just stacks, but systems!
    - Balance of plant/auxiliary system development and refinement
    - WTM, optimized air compressors, startup issues, etc
  - Refueling infrastructure for hydrogen
  - Cost, cost, cost (FC system target of \$40-50/kW!)
  - Durability, durability, durability (~4,000 hours)



# Stationary Fuel Cells

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- Why Stationary Fuel Cells?
  - Cleaner and more efficient than most DG options
  - Quiet operation
  - Some types offer high-grade waste-heat
  - Highly reliability/availability(?)
  - Modularity should lend itself to cost reduction (many repeat components)



# Stationary Fuel Cells

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- Key Industry Players
  - PAFC: United Technologies (formerly IFC)
    - ~200 200-kW units sold, mostly in U.S. and many under DoD buydown program (~\$4K/kW - \$1K/kW)
  - PEM: Ballard, United Technologies, Plug Power
    - Intense activity and lots of players, new Ballard/Coleman 1.2 kW unit (about \$6K/kW)
  - SOFC: Siemens - Westinghouse
    - Years of development but still problems with cell to module scale-up? (seals and materials)
  - MCFC: Fuel Cell Energy
    - Commercial product, 60 MW in orders for 2003



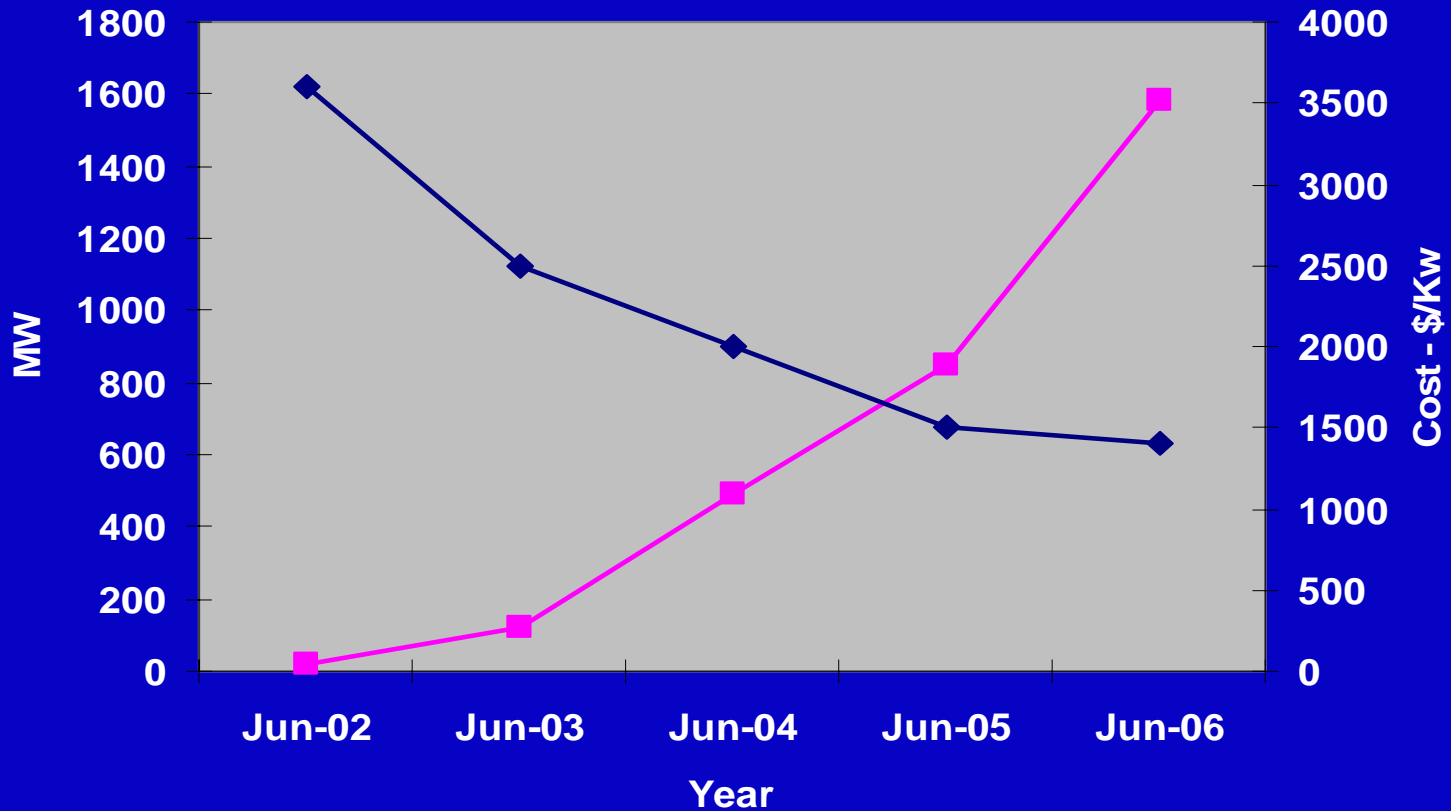
# Stationary Fuel Cells

Technology Provider	FC Type	Deployment Time Frame by Net System Power and (Fuel Type)			Primary Application
		6 months	12 months	18 to 24 months	
H2 ECONomy	PEMFC	0.05 kW (H2)	1 kW (H2)	1 kW (H2)	Portable Elect. / Light Residential
Ballard Power Systems	PEMFC	1.2 kW (H2)	1.2 kW (H2)	10 kW (NG) 60 kW (H2)	Portable for OEM Products Residential / Light Commercial
IdaTech, LLC	PEMFC	1 kW (M100) 3 kW (M100)	1 kW (M100) 3 kW (M100)	1 kW (M100) 3 kW (M100)	Portable / Residential / Light Commercial
Anuvu Inc.	PEMFC	1 to 5 kW (H2)	1 to 5 kW (H2)	1 to 5 kW (H2)	Remote Off-Grid
Plugpower, Inc.	PEMFC	5 kW (NG)	5 kW (NG, H2)	50 kW (H2)	Residential / Light Commercial
Nuvera Fuel Cells	PEMFC	5 kW (NG, LPG)	5 kW (NG, LPG)	5 kW (NG, LPG)	Telecomm / Datacomm
DCH Technology, Inc.	PEMFC	1,3,5,10 kW (NG, H2)	20 kW (NG, H2)	40 kW (NG, H2)	Residential / Light Commercial
UTC Fuel Cells	PAFC	200 kW (NG, LPG)	200 kW (NG, LPG)	200 kW (NG, ADG)	Residential / Light Commercial Commercial CHP
	PEMFC	Unclear Timing	Unclear Timing	150-200 kW (NG)	
Energy Alternatives (Systems Integrator)	SOFC	No Demo Product	5 kW (LPG)	5 kW (LPG)	Remote Off-Grid Commercial CHP
				250 kW (NG)	
Siemens Westinghouse	SOFC	No Demo Product	Unclear Timing	250 kW (NG)	Commercial CHP, Small-Scale DG
Shell Hydrogen / Siemens Westinghouse	SOFC	No Demo Product	No Demo Product	250 kW CO <sub>2</sub> sequestering (NG, LSD, MD, LPG)	Commercial CHP, Small-Scale DG
FuelCell Energy, Inc.	MCFC	Unclear Product Availability (sold out / order back log)	250 kW (NG, ADG) 1 MW (NG, ADG)	250 kW (NG, ADG, LPG) 1 MW (NG, ADG, LPG) 2 MW (NG, ADG, LPG)	Industrial Co-Gen and Medium- to Large-Scale DG

Source: CaSFCC



# Stationary Fuel Cells



Source: CaSFCC

—■— MW —◆— Cost (\$/kW)



# Stationary Fuel Cells

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## Plug Power Residential PEMFC Prototype

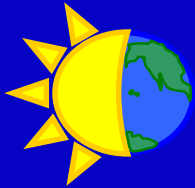




# Stationary Fuel Cells

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- Key Issues
  - Integration with Utility Grids
  - Reasonable Standby/Exit Fees
  - Durability, durability, durability (~40,000 hours)
  - Cost, cost, cost (FC system target of ~\$700-800/kW)



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# **Economic Analysis of Hydrogen Energy Station Concepts:**

**Are “H2E-Stations” a Key Link to a  
Hydrogen Fuel Cell Vehicle Infrastructure?**

**October 30, 2002**

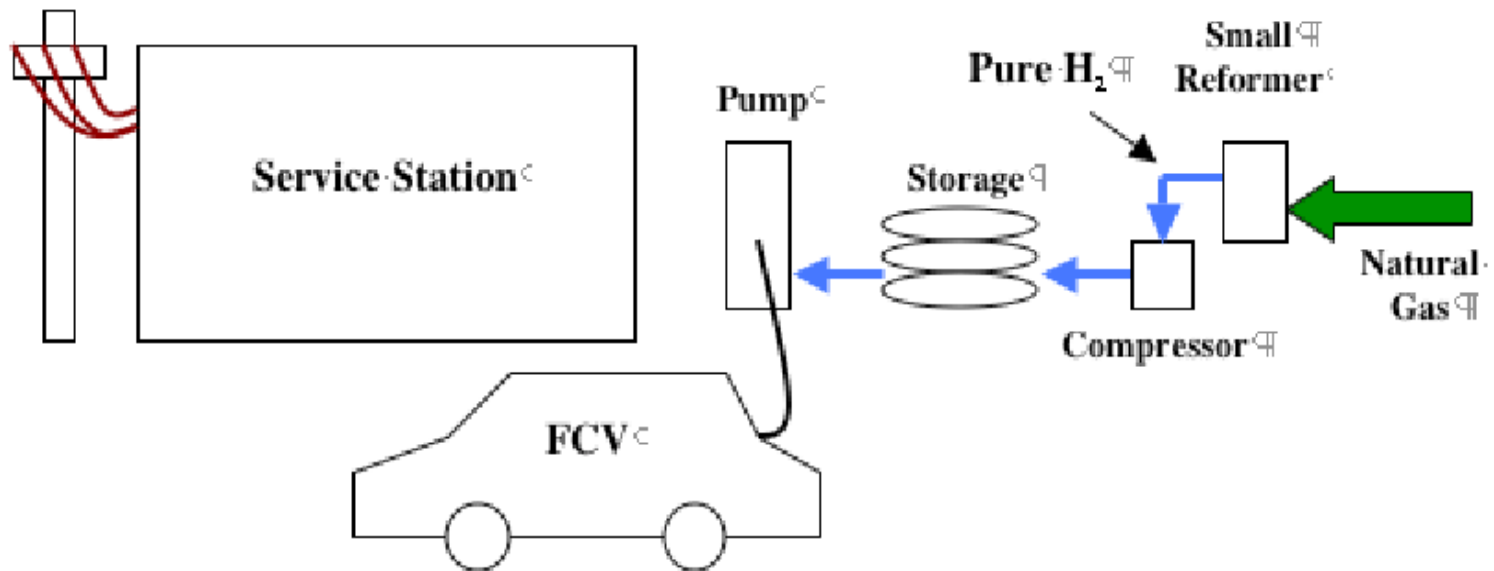
**Prepared for:  
BP and DaimlerChrysler**

**Dr. Timothy E. Lipman  
Ms. Jennifer L. Edwards  
Prof. Daniel M. Kammen**



# H2E-Stations vs. H2 Stations

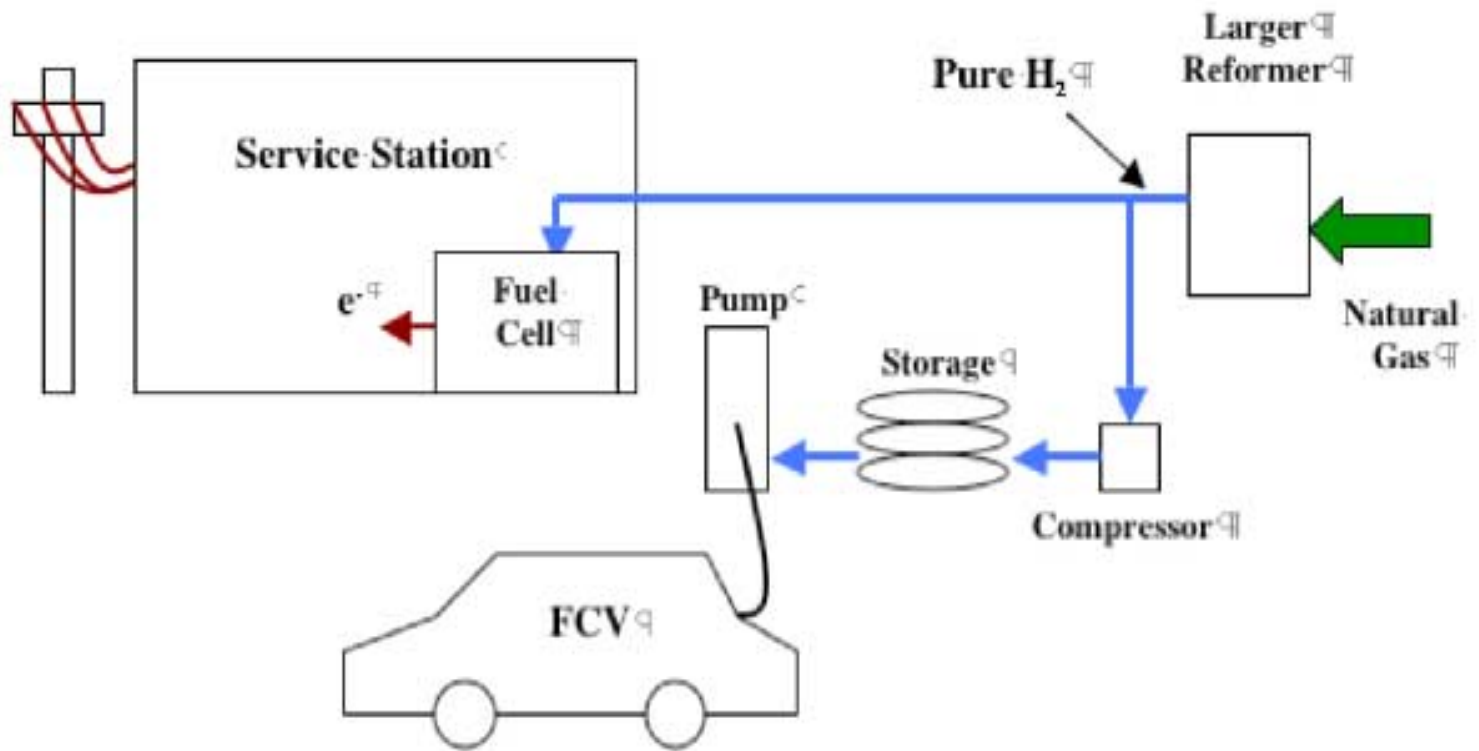
## Service Station Scenario 1: H<sub>2</sub> Station





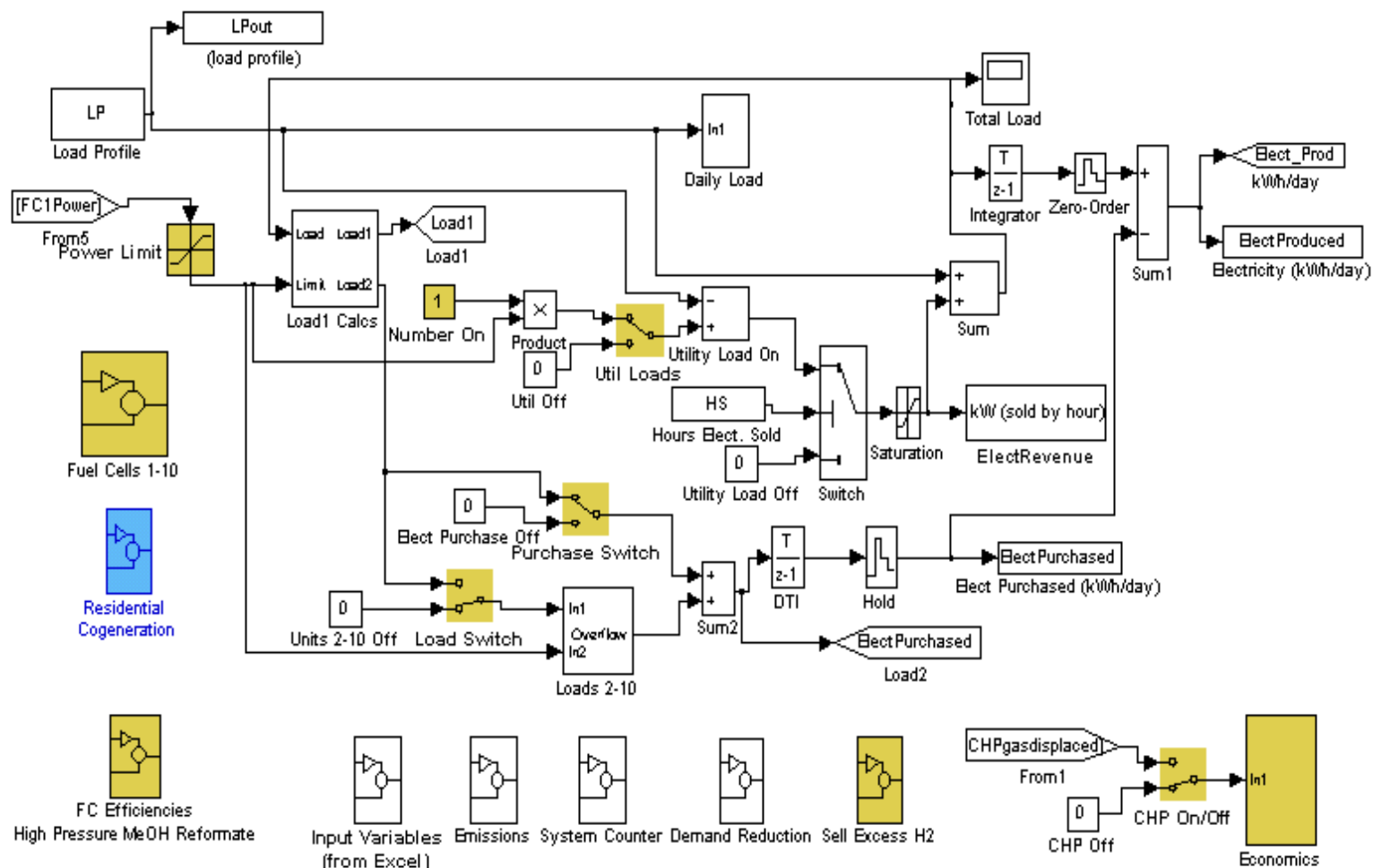
# H<sub>2</sub>E-Stations vs. H<sub>2</sub> Stations

Service Station Scenario 2: H<sub>2</sub>E-Station



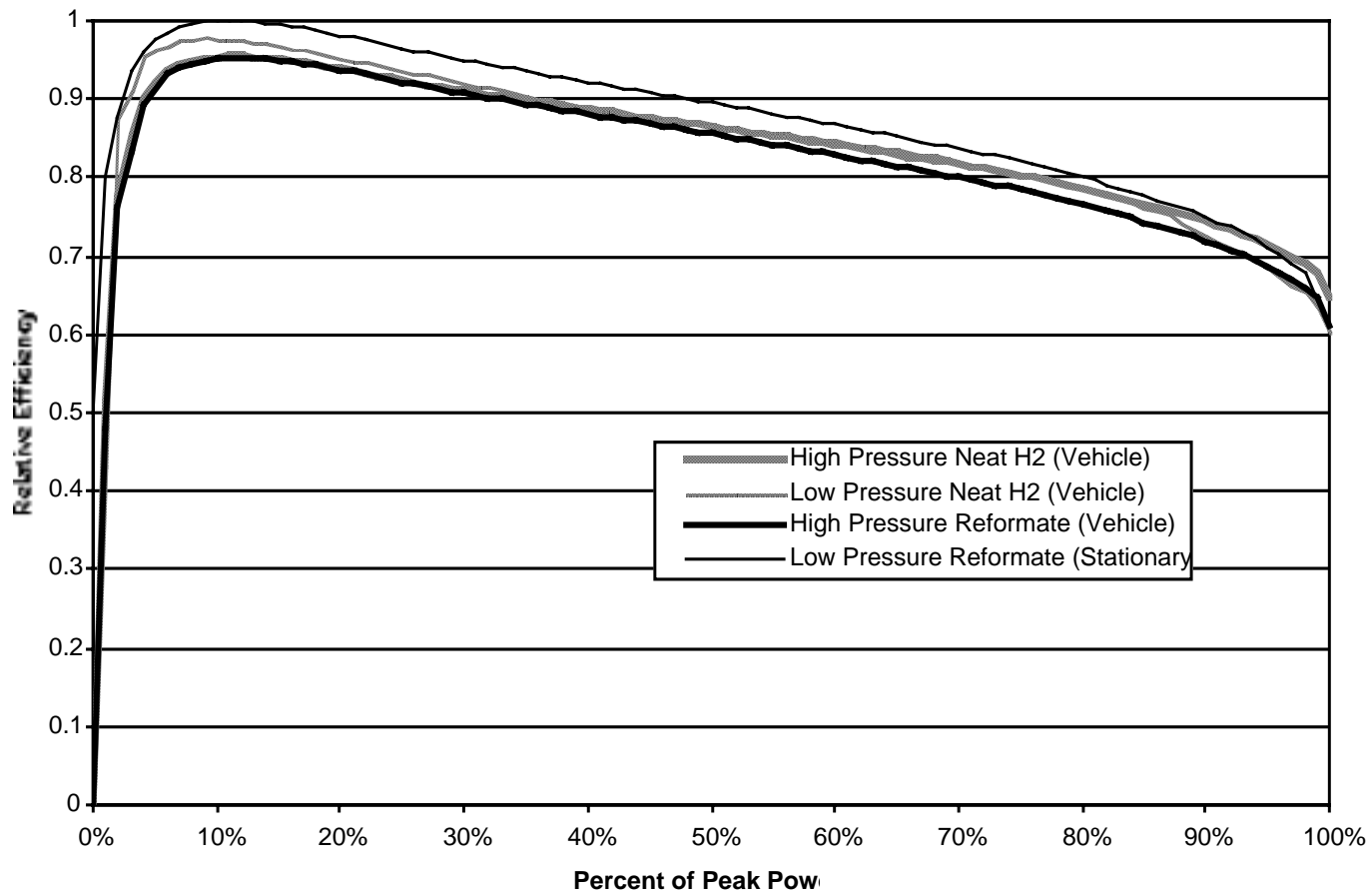


# MATLAB/Simulink Model



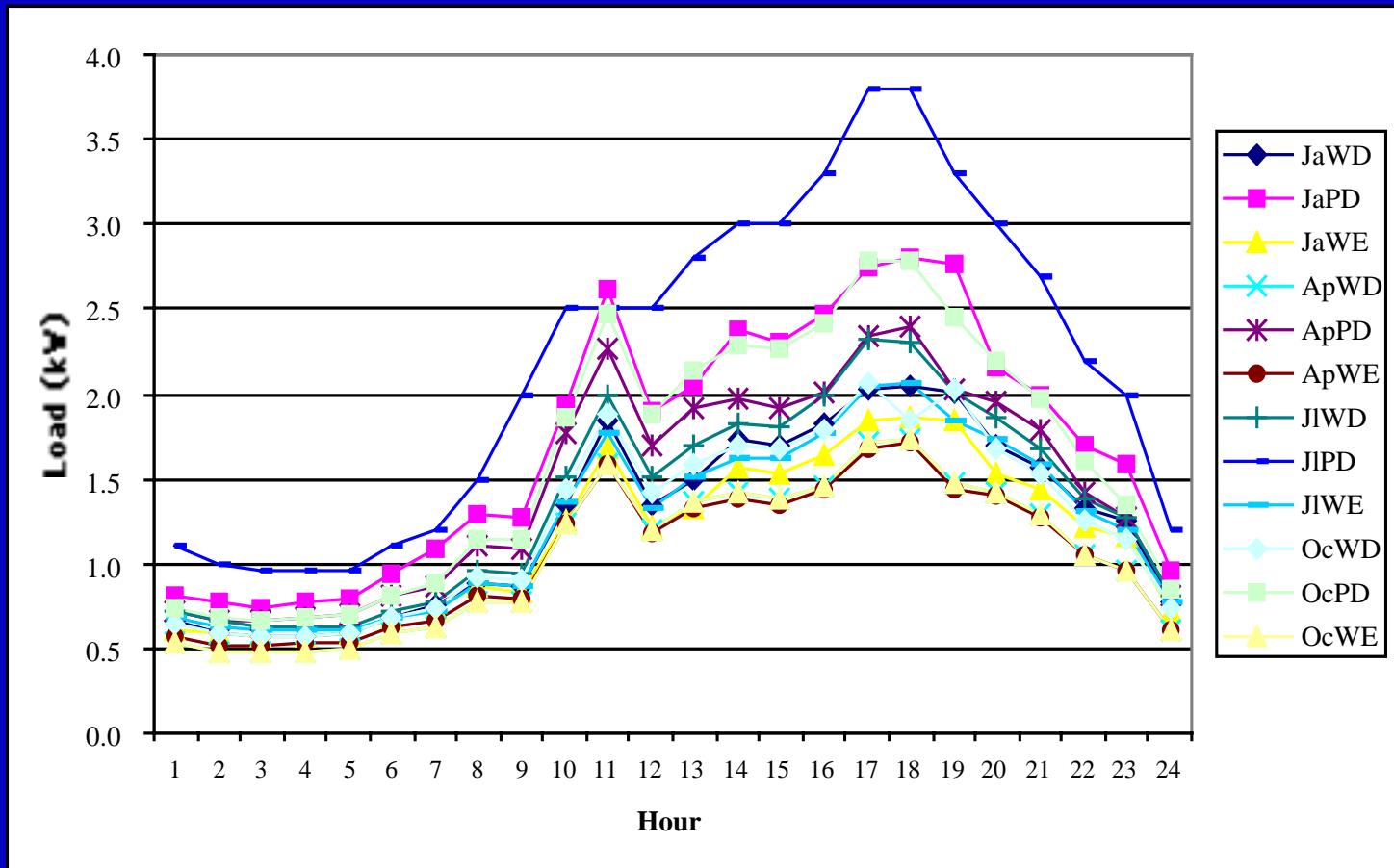


# MATLAB/Simulink Model



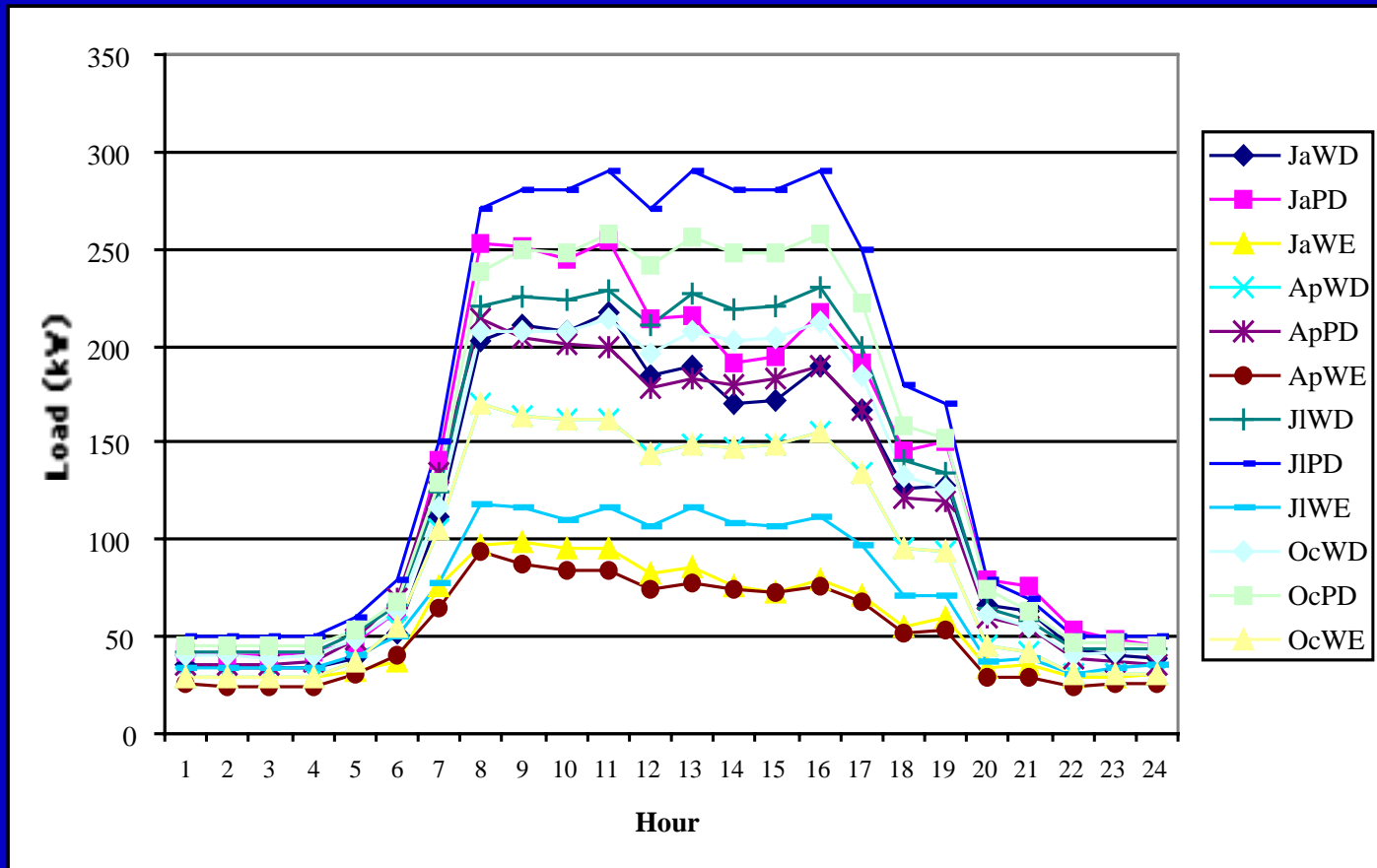


# Large CA Residential Loads





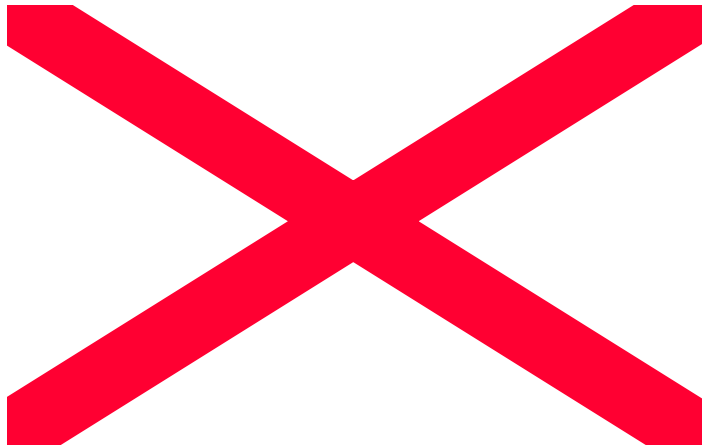
# Medium-Sized CA Office Building Loads

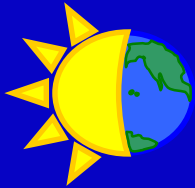




# H2-E Station Analysis

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# H2-E Station Analysis

Costs and Revenues Included in the Analysis	Costs and Revenues Not Included in the Analysis
<ul style="list-style-type: none"><li>• Fuel cell system capital costs</li><li>• Natural gas reformer capital costs</li><li>• Capital costs for FCV refueling equipment, including H<sub>2</sub> compressor, H<sub>2</sub> storage, and H<sub>2</sub> dispensing pump</li><li>• Natural gas fuel costs for electricity and hydrogen production</li><li>• Fuel cell system annual maintenance and periodic stack refurbishment</li><li>• Reformer maintenance</li><li>• Purchased electricity, including fixed monthly charges, energy charges, and demand charges</li><li>• Revenues from hydrogen sales to FCVs</li><li>• Avoided electricity costs due to self-generation</li><li>• Avoided natural gas costs due to co-generation of hot water with fuel cell system waste heat</li></ul>	<ul style="list-style-type: none"><li>• Equipment installation costs</li><li>• Safety equipment costs</li><li>• Costs of any required construction permits or regulatory permits</li><li>• Costs associated with any property that is devoted to FCV refueling</li><li>• Utility “standby charges” for providing backup for electricity self-generation</li><li>• Costs of any labor associated with energy station operation or administration</li><li>• Federal, state, and local taxes on corporate income, including tax credits for equipment depreciation, etc.</li><li>• Revenues from government incentives for fuel cell installation/operation or hydrogen dispensing</li></ul>

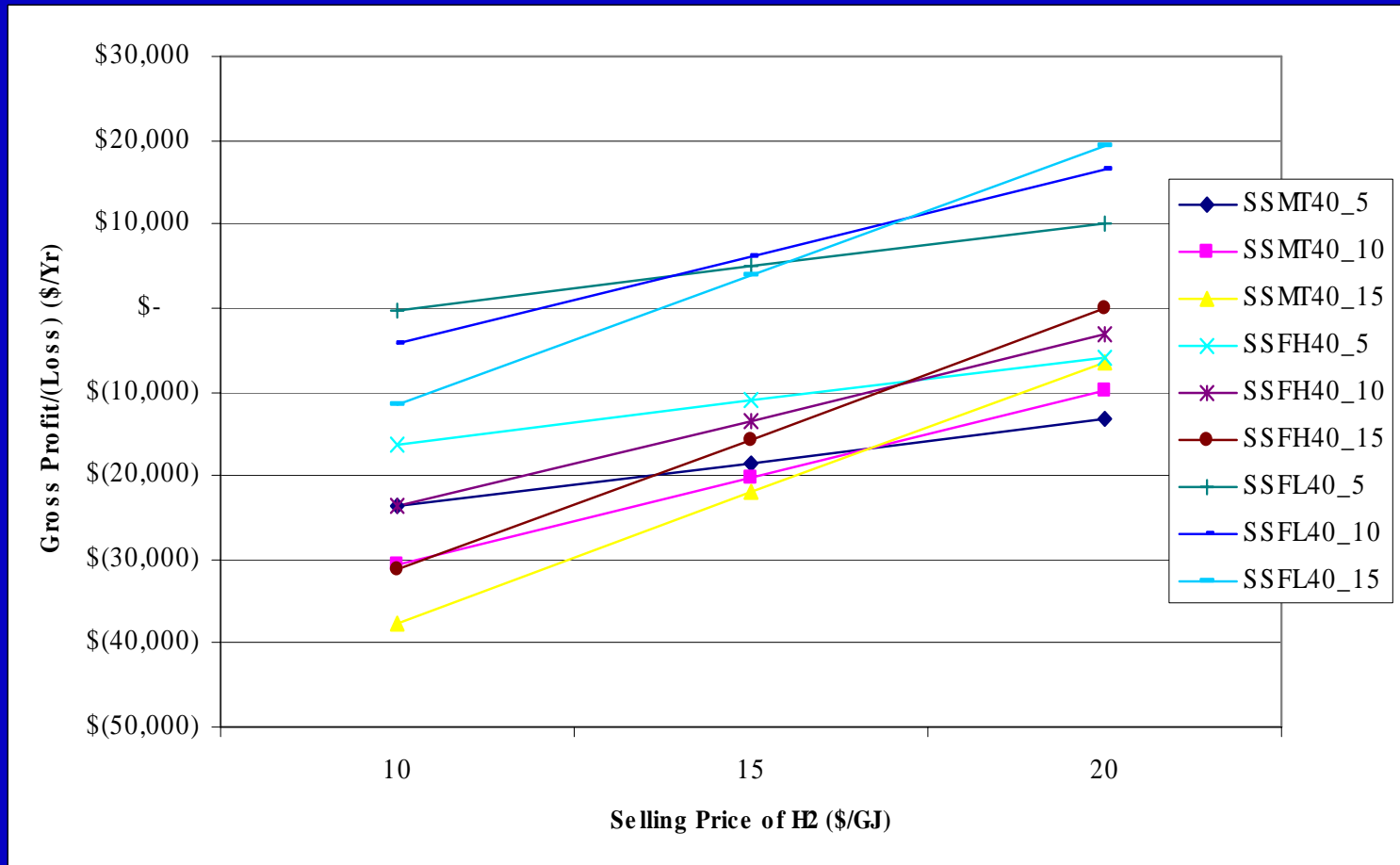


# H2-E Station Analysis

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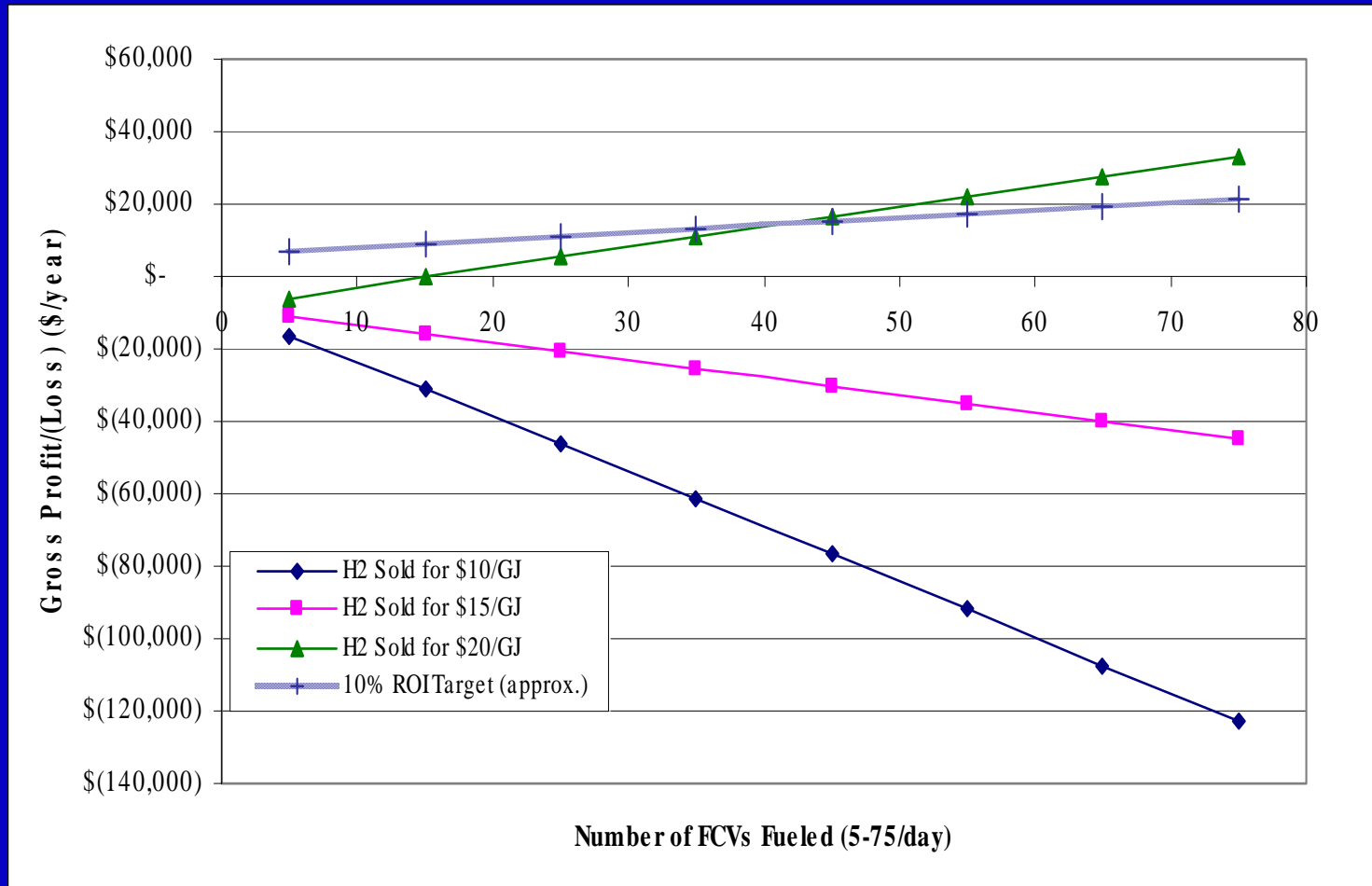
- Two Settings:
  - Service Station w/25kw and 40 kW fuel cells and 5-75 vehicles/day
  - Office Building w/50-250 kW fuel cells and 10 vehicles/day
- Various economic assumptions, but future FC costs (on the order of \$500-1,000/kW)

# Sample Results: H2-E Service Station w/40 kW fuel cell

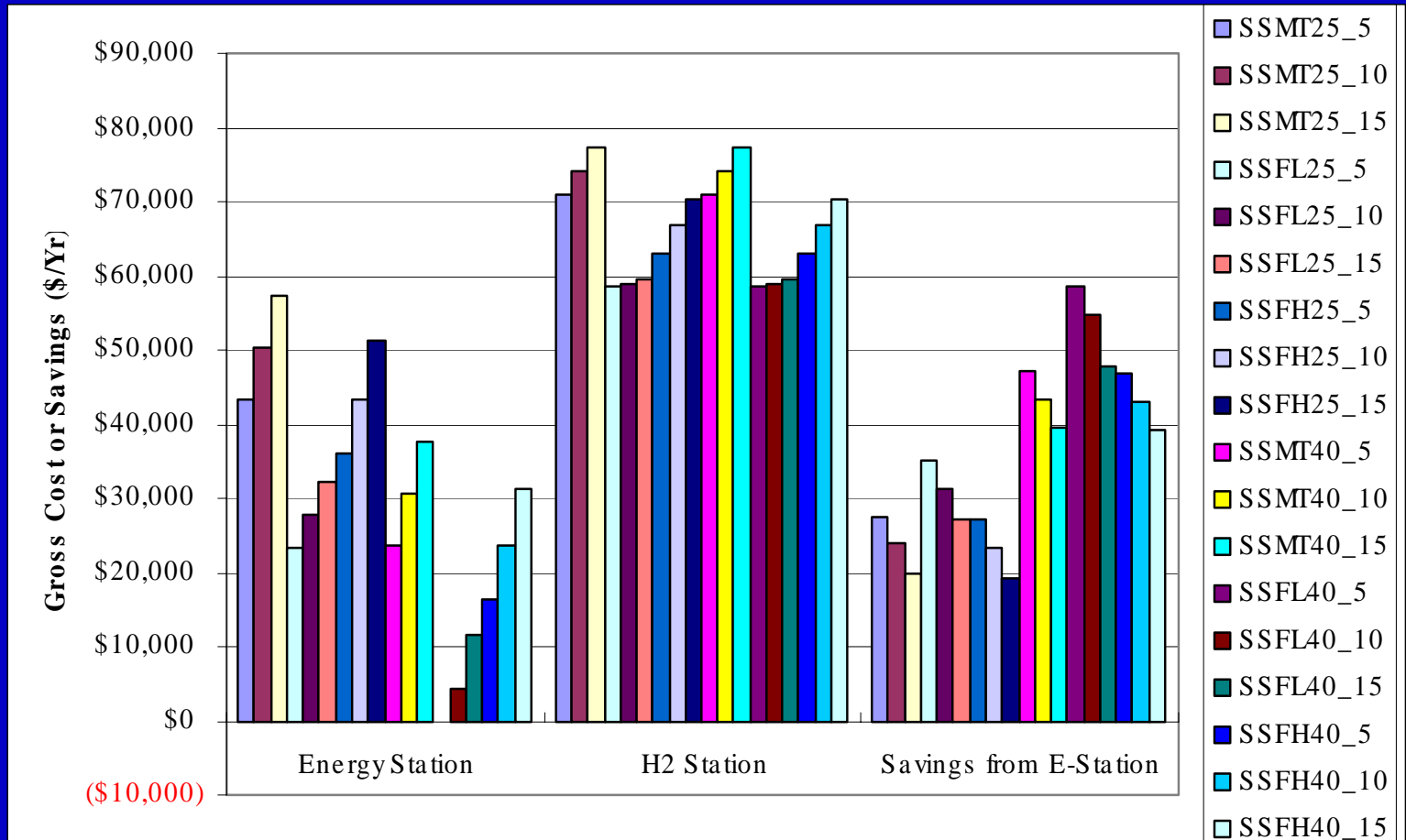


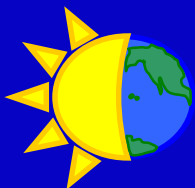


# Sample Results: H2-E Service Station w/40 kW fuel cell and “future high” cost

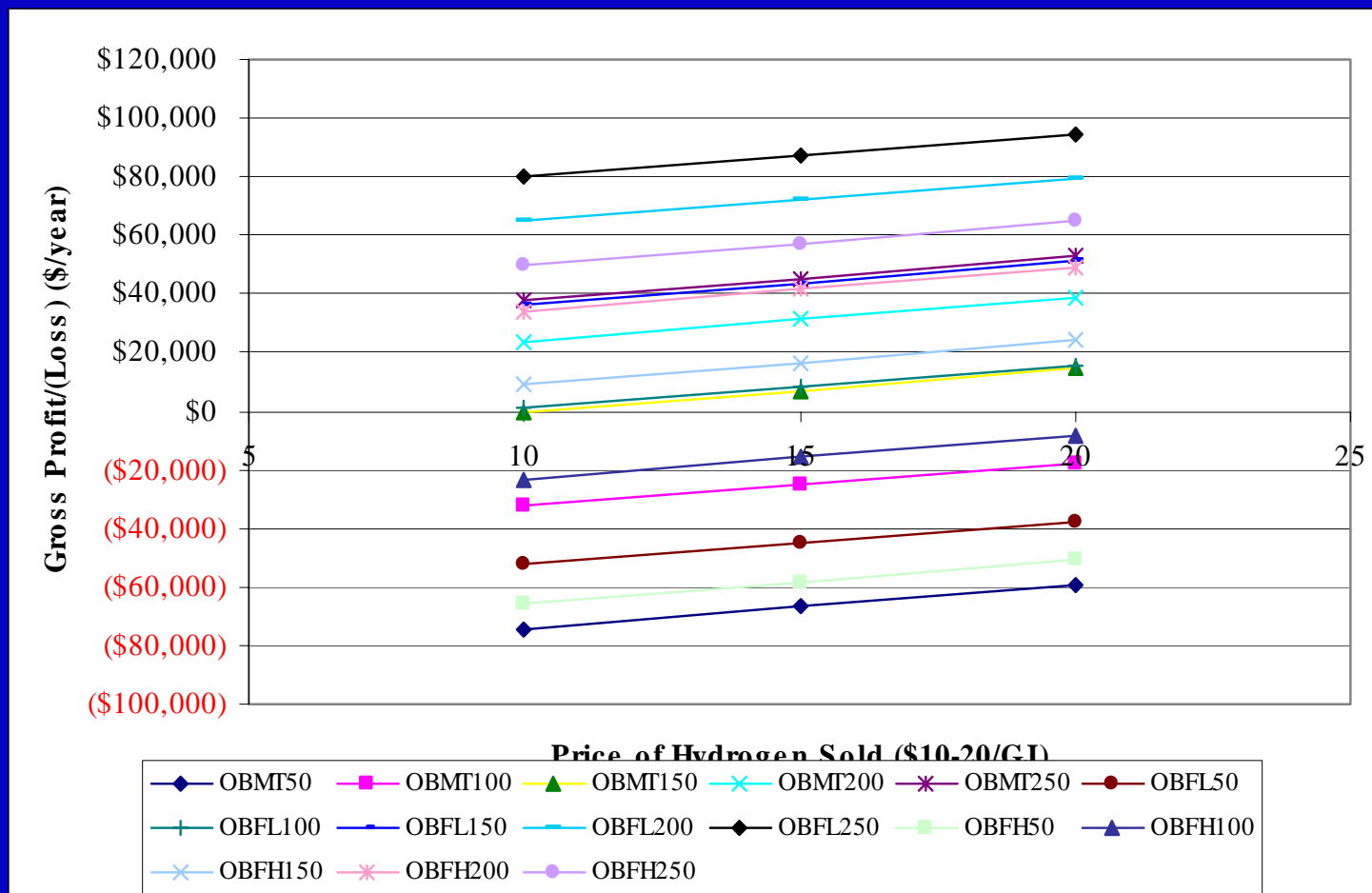


# Sample Results: H2-E Service Station vs. H2 Service Station Designs





# Sample Results: H2-E Office Building





# H<sub>2</sub>E-Station Findings

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- The economics of supporting small numbers of FCVs, on the order of 5-15 per day, are difficult and only under the most favorable circumstances can fueling stations break even or turn a small profit.
- However, the losses associated with supporting early FCVs with hydrogen fueling can potentially be reduced by employing H<sub>2</sub>E-Station designs.
- The economics of “office building” H<sub>2</sub>E-Stations appear favorable relative to “service station” H<sub>2</sub>E-Stations, once fuel cell and H<sub>2</sub> equipment becomes mass produced and less expensive, and where the economics of producing electricity and displacing grid purchases are favorable.



# H2E-Station Findings (cont'd)

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- In cases where 50 to 75 FCVs per day are supported in service station H<sub>2</sub>E-Station designs with a 40 kW fuel cell and “future high” cost estimates, a 10% ROI target can be achieved but only with hydrogen sold at or near \$20 per GJ.
- With lower natural gas prices than \$6/GJ, the prospects for economic sales of hydrogen at closer to \$15/GJ would brighten.





# Vehicle-to-Grid Power

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- Huge Potential Resource
  - Total shaft power of motor vehicles is ~14 times the electricity generating capacity of U.S.
  - Vehicles are only in use for about 1 hour per day on average
  - 13,140 GWh per year (~1.5 GW on average) per 100,000 FCVs, assuming 30 kW per vehicle and 50% vehicle availability



# Vehicle-to-Grid Power

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# Vehicle-to-Grid Power

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- Residential Setting
  - Single hybrid or non-hybrid vehicle with small, off-board natural gas SMR or ATR unit
  - 6 PM to 8 AM availability, 300 days/year
  - Local load (avg. 1.2 kW) plus net-metering scenarios
  - Natural gas @ \$4, \$6, and \$10 per MBTU
  - Electricity prices of \$0.10-0.15/kWh, plus TOU rates



# Vehicle-to-Grid Power

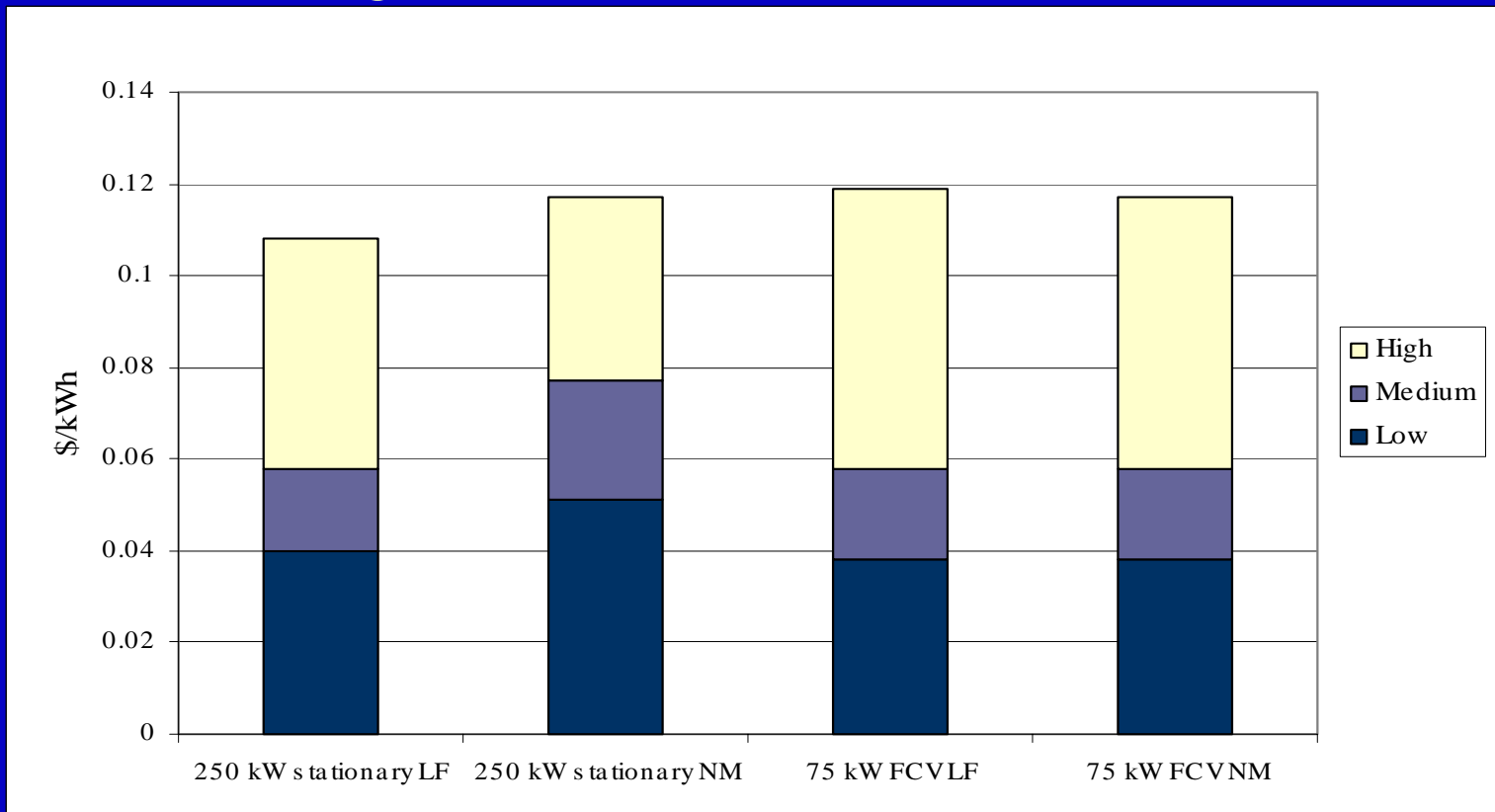
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- Commercial Setting -- Office Building
  - Up to 10 FCVs with a larger industrial grade SMR unit
  - 8 AM to 6 PM availability, 250 days per year
  - Building load from ~30 to ~300 kW
  - \$7-12/kW demand charge and \$0.05-0.08/kWh electricity, plus TOU rates
  - Natural gas @ \$3, \$4, and \$6 per MBTU



# Vehicle-to-Grid Power

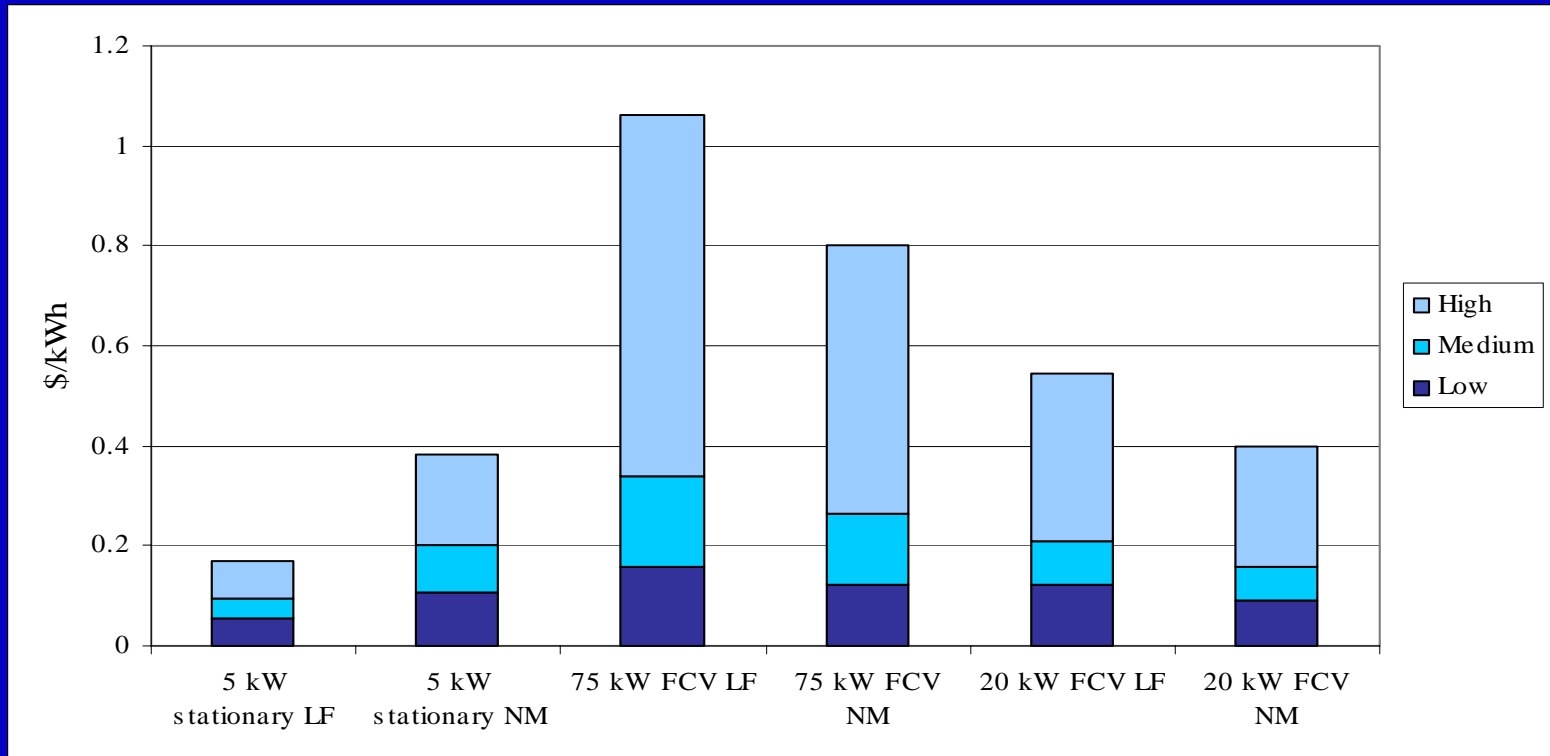
## Office Building Results





# Vehicle-to-Grid Power

## Residential Building Results





# FCV-to-Grid Findings

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- FCVs are Promising as DG Resources, but Several Important Issues Must be Resolved
- Use in Residential Settings Will Benefits From Net Metering or Community-Based System
- Use in Commercial Settings is Attractive Due to Potential for Demand Reduction, Use During Period of Grid Peak (3-6pm), and Access to Lower Cost Natural Gas
- Research is Ongoing to Further Understand Key Sensitivities and Optimal Settings/Strategies



# New UCB DER Center: CIDER

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- CIDER Plan:
  - Initial Launch in November 2002, Full Operations by June 2003
  - Five main areas:
    - 1) the economics of DER/CHP technologies
    - 2) the air pollutant and GHG emissions impacts of DER/CHP technologies
    - 3) renewable DG systems based on wind turbines, solar photovoltaics (PV), biomass, small hydro, and tidal power (RAEL, <http://socrates.berkeley.edu/~rael>);
    - 4) electricity demand-response technologies/economics
    - 5) hydrogen as a fuel/energy carrier for DER technologies
  - Office at 2105 Bancroft Way, Suite 300